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<p>Two drop/gas interactions important in the near-injector dense region of sprays are being studied:</p> <p>(1) turbulence modulation, which is the direct generation or modification of turbulence by drop motion, and</p> <p>(2) secondary drop breakup, an important rate-controlling process in dense sprays. Effects of turbulence modulation were measured in homogeneous flows generated by particles falling in stagnant air and water baths. The flow was analyzed with a simple stochastic approach, involving linear superposition of randomly-arriving particle velocity fields. Guided by the theory, unified correlations of turbulence properties were achieved for the measurements. Further progress requires more information about particle wake properties at modest Reynolds numbers in turbulent fields: this is the main focus of current work.</p> <p>Secondary drop breakup is being studied using a shock tube and various drop generators, emphasizing near-limit breakup which is most relevant to dense sprays. Work thus far has concentrated on definition of deformation and shear breakup regimes. This will be followed by study of breakup dynamics and outcomes using holocinematography instrumentation that was recently developed in this laboratory.</p>					
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## INTRODUCTION

Sprays and spray processes have been studied extensively due to numerous applications. This has resulted in significant progress toward understanding and modeling processes within the dilute portions of sprays. However, existing information concerning the near-injector dense-spray region is very limited so that phenomena which control initial conditions for the dilute spray region are not understood. Thus, the overall objective of the present investigation is to contribute to a better understanding of aspects of dense sprays.

Present research goals were motivated by findings of an earlier Air Force sponsored investigation (AFOSR 85-0244). The earlier study involved measurements of the structure of large-scale pressure-atomized sprays using holography to observe the properties of the dense-spray region. For the important atomization breakup regime, the flow near the injector exit involves a liquid core, similar to the potential core of single-phase jets, surrounded by a multiphase mixing layer. The multiphase mixing layer is surprisingly dilute, with large relative velocities between the phases and nearly uniform mean gas-phase velocities. Thus, the turbulence properties within the multiphase mixing layer are largely governed by drop motion through the gas (effects which have been termed turbulence modulation), rather than conventional mechanisms found in single-phase mixing layers. Similar conditions are encountered over much of the combustion chamber of liquid rocket engines and even in natural phenomena like rainstorms. In spite of these applications, however, turbulence modulation has not received much attention the past and its study constitutes one phase of the present investigation.

The earlier observations also showed that the multiphase mixing layer consisted of large irregular liquid elements near the liquid surface, which evolved to smaller round drops over the rest of the flow. This supports the classical view of liquid atomization — primary breakup into large drops and ligaments near the liquid surface followed by secondary breakup into smaller round drops. Additionally, it was found that secondary breakup becomes the rate-controlling process within dense sprays at the high pressures of most practical applications, much like the decay of relative velocities and drop vaporization are rate-controlling processes for dilute sprays. Finally, the outcome of primary breakup yielded drops that were near the secondary drop breakup limit. Unfortunately, near-limit secondary breakup phenomena have not received much attention, aside from defining the conditions for the limit itself. The major deficiency is definition of the outcome of breakup which is needed to define initial conditions for the dilute-spray region. Thus, study of near-limit secondary breakup constitutes the second phase of the present investigation.

## RESEARCH OBJECTIVES

Specific objectives of the turbulence modulation and secondary breakup phases of the study can be summarized as follows:

1. Turbulence Modulation: (i) Complete measurements of the structure of homogeneous particle-laden flows in both air and water, and (ii) develop a stochastic analysis of the flow, accounting for the random arrival of particles (drops), to help interpret the measurements.
2. Near-Limit Secondary Breakup: (i) Complete measurements of secondary breakup to define breakup regimes, rates and outcomes, and (ii) employ phenomenological theories to develop effective correlations of the data.

## ACCOMPLISHMENTS

### Turbulence Modulation

Earlier measurements of homogeneous particle/water flows (under AFOSR 85-0244) were extended to particle/air flows, and all the results were successfully correlated using a stochastic theory. The measurements involved uniform fluxes of round glass beads settling in a stagnant (in the mean) air bath, with continuous-phase turbulence properties being measured using two-point phase-discriminating laser velocimetry. Predictions were based on simplified stochastic analysis, extending classical analysis of random noise from the theory of signal processing. This involved linear superposition of randomly-arriving particle velocity fields. The motivation for considering both particle/air and water flows is that this provides a large range of dissipation rates of particle mechanical energy which the theory suggested was a dominant flow-variable.

The theory provided rather successful correlations of relative turbulence intensities (referenced to mean particle relative velocities) and probability density functions of velocity fluctuations. These results indicated that turbulence levels were dominated by the rate of dissipation of particle energy with particle drag properties being a secondary factor. Additionally, normalized probability density functions, spatial correlations and temporal spectra are largely independent of dissipation rates and particle properties — in accord with predictions. The flows exhibited several unusual features in comparison to conventional homogeneous turbulence fields: they were strongly anisotropic with streamwise velocity fluctuations being roughly twice crosstream velocity fluctuations; temporal spectra had a large range of frequencies even though particle Reynolds numbers were modest (30-800) and the spectra decayed according to the  $-1$  power rather than the  $-5/3$  power of frequency; and spatial integral-scales were large and were not related to the mean separation distances of the particles. The theory showed that most of these curious properties are due to the dominance of mean velocities of randomly-arriving particle wakes on the structure of the flow.

The theory is helpful, however, it has several serious deficiencies. The main problem is that integrations of particle wake properties needed for predictions diverge slowly with distance from the particle and must be terminated in an *ad hoc* manner to match measurements of relative turbulence intensities (at 175 diameters from the particle where velocity defect of the wake was small in comparison to levels of velocity fluctuations). Similar difficulties have been encountered during the stochastic analysis of sedimentation but they could be resolved based on rigorous knowledge of the properties of Stokes flow. Unfortunately, the Reynolds numbers of drops in sprays are too high for this approach to be useful for present flows.

A second difficulty is that predictions of spatial correlations and integral scales are not very effective. In general, predictions of crosstream and streamwise length scales are too small and too large, respectively. A near-term solution of this problem involved empirical fitting of correlations and phenomenological analysis to find effective correlations of integral scales, similar to treatments of other homogeneous turbulent flows.

The convergence and spatial correlation problems of the theory raise questions concerning current fundamental understanding of the flow and the application of present findings to practical dense sprays. The main problem is that wake properties required for predictions were obtained from measurements at higher Reynolds numbers than present conditions, which do not consider effects of transient eddy shedding at modest Reynolds numbers or effects of ambient turbulence. Both these effects should increase wake mixing rates, potentially resolving problems of convergence and spatial correlations. Thus,

emphasis is now being placed on the properties of particle wakes at modest Reynolds numbers in turbulent environments to see if this conjecture is correct.

Particle wake properties are being addressed by developing a new test apparatus. This involves a stagnant (in the mean) bath as before, but with a single test sphere being driven through the bath by a traversing mechanism. In order to have reasonable sphere sizes and wake velocity levels, while simulating the appropriate Reynolds number range, solutions of glycerin and water are being used as the bath liquid. Tests will involve both still and turbulent bath liquid, the latter being generated by traversing grids through the bath before traversing the sphere. Two-point laser velocimetry will be used to characterize bath turbulence properties and complete initial measurements of mean properties of the wakes. However, the bulk of the measurements will involve particle image velocimetry (PIV) which has been developed during other work in this laboratory. Design and fabrication of this apparatus are nearing completion, with measurements and theoretical interpretation of the results to be carried out during the next report period.

Near-Limit Secondary Breakup. Results in the literature provide some information on drop breakup regimes. Most workers have found that near-limit breakup involves large-scale deformation of the drop, leading to bag breakup and other similar modes where portions of the drop are blown up into thin balloon-type structures before shattering. However, this regime is rather narrow so that increases of relative velocities lead to shear or stripping breakup where liquid leaves from the periphery of the drop. Currently, there is substantial information available concerning transition to deformation breakup, however, the shear breakup transition is not well defined. Thus, present work has begun by studying transitions to particular breakup regimes, with consideration of the dynamics and outcomes of breakup events to follow.

The test apparatus involves a shock tube with the driven section initially at atmospheric pressure. Rayleigh breakup and vibrating diaphragm drop generators are used, with the drop stream passing across a windowed section of the driven tube. The breakup of drops in the flow behind the shock wave is observed by stroboscopic backlighting with a copper vapor laser and is recorded using a nonframing camera.

Initial measurements considered the deformation breakup limit in order to test apparatus performance and our interpretation of drop shattering events. These results were in good agreement with observations in the literature so that current work is considering the shear breakup transition. Effects of large Ohnesorge numbers (due to low surface tension), that are relevant for sprays near thermodynamic critical conditions, are of particular interest. Large Ohnesorge numbers are known to influence deformation breakup limits but their influence on shear breakup is unknown.

Other work to be carried out during the next report period involves studying the dynamics and outcome (drop sizes and velocities) of breakup events. This will be done using holocinematography to obtain three-dimensional time-resolved images of the flow. The holocinematography instrument was developed in this laboratory and provides a 35mm diameter x 70mm long object field at rates up to 8000 holograms per second with capabilities for record lengths up to 70 holograms. The availability of this instrument provides an unusual opportunity to resolve long standing issues about the character of secondary breakup.

## PUBLICATIONS

M. Mizukami, R.N. Pathesarathy and G.M. Faeth (1990) Particle-generated turbulence in homogeneous dilute dispersed flows. Submitted to J. Fluid Mechanics.

G.A. Ruff, P.-K. Wu, L.P. Bernal and G.M. Faeth (1990) Continuous-and dispersed-phase structure of dense nonevaporating pressure-atomized sprays. AIAA Paper No. 90-0464, also submitted to J. Propulsion and Power [A portion of this work was performed under AFOSR 85-0244].

G.M. Faeth (1990) Structure and atomization properties of dense turbulent sprays. Twenty-Third Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, in press [A portion of this work was performed under AFOSR 85-0244].

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1. Continuous-phase turbulence properties. Bull. Amer. Phys. Soc. 34, 2312.

G.M. Faeth and R.N. Parthesarathy (1989) Homogeneous particle-laden flows:  
2. Turbulent dispersion. Bull. Amer. Phys. Soc. 34, 2312.

#### PERSONNEL

Prof. G.M. Faeth	Principal Investigator	9%
Mr. G.A. Ruff	Ph.D. Student	50% (89/8-89/12)
Mr. M. Mizukami	M.S. Student	50% (89/9-90/5)
Mr. L.-P. Hsiang	Ph.D. Student	50% (90/1-)
Ms. H. Younis	Ph.D. Student	50% (90/5-)

#### ADVANCED DEGREES AWARDED

R.N. Parthesarathy, "Homogeneous Dilute Particle-Laden Water Flows," Ph.D. Thesis, The University of Michigan, December 1989.

G.A. Ruff, "Structure and Mixing Properties of the Near-Injector Region of Nonevaporating Pressure-Atomized Sprays," Ph.D. Thesis, The University of Michigan, June 1990.

#### ORAL PRESENTATIONS

G.M. Faeth, "Separated Flow and Breakup Phenomena in Dense Sprays," ASME Workshop on Challenging Issues in Heat and Mass Transfer in Spray Systems, Philadelphia, PA, August 1989 (invited).

G.M. Faeth, "Structure of Dense Pressure-Atomized Sprays," Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, PA, September 1989 (invited).

G.M. Faeth, "Stochastic Aspects of Turbulent Combustion Processes," Mathematics in Chemistry Conference, Texas A & M University, College Station, TX, November 1989 (invited).

G.M. Faeth, "Progress Concerning Dense Spray Processes," International Liquid Atomization and Spray Systems Conference, Hartford, CT, May 1990 (invited).

G.M. Faeth, "Drop/Gas Interactions in Dense Sprays," AFOSR/ONR Contractors' Meeting in Propulsion, Georgia Institute of Technology, Atlanta, GA, June 1990.

G.M. Faeth, "Atomization and Mixing in Dense Turbulent Sprays," Twenty-Third Symposium (International) on Combustion, Orlean, France, July 1990 (invited).

R.N. Parthasarathy, "Homogeneous Particle-Laden Flows: 1. Continuous-Phase Turbulence Properties," APS/DFD Meeting, Palo Alto, CA, November 1989 (contributed).

G.M. Faeth, "Homogeneous Particle-Laden Flows: 2. Turbulent Dispersion," APS/DFD Meeting, Palo Alto, CA, November 1989 (contributed).

G.M. Faeth, "Continuous-Phase Properties of the Near-Injector Region of Pressure-Atomized Sprays," AIAA 28th Aerospace Sciences Meeting, Reno, NV, January 1990.

#### INVENTIONS

None.

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